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By J. F. McIlwain and L. A. Neumeier



UNITED STATES DEPARTMENT OF THE INTERIOR



Report of Investigations 9105

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Donald Paul Hodel, Secretary**

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere	min	minute
m ³ /min	cubic meter per minute	μm	micrometer
mg/m ³	milligram per cubic meter	pct	percent
mg/min	milligram per minute	s	second
mm	millimeter	V	volt
mm/min	millimeter per minute	wt pct	weight percent

FUMES FROM SHIELDED METAL ARC WELDING ELECTRODES

By J. F. McIlwain¹ and L. A. Neumeier¹

ABSTRACT

The Bureau of Mines has investigated fumes generated by selected welding electrodes used in mines in order to help determine their relative health hazard potential. Fumes were generated and collected in an enclosed chamber for subsequent generation rate and chemical constituent determination. Shielded metal arc electrodes from the following groups were tested: AWS types E308-16 and E310-16 stainless steel, ECoCr-A Co-Cr hardfacing alloy, ENiCr Ni, an Mn-Cr buildup alloy, E7018 carbon steel, and E11018-M low-alloy steel. Flux-cored wire electrodes of this last group also were tested. Fume generation rates and the chemical composition of the fumes were measured. From these data, exposure indices were determined, which give a relative measure of the health hazard potential of using the electrodes. The effect of welding onto build-up alloy layers on the fume composition also was examined for five of the higher alloy groups.

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INTRODUCTION

Exposure to welding-fume particulates by workers in the mining industry is of concern to the Mine Safety and Health Administration (MSHA), U.S. Department of Labor, as well as to mining industry personnel. Because welding may frequently be conducted in closed or confined quarters, the possibility exists of overexposure to fumes² due to inadequate ventilation. Fumes from various types of electrodes are known to contain, or are suspected to contain, potentially hazardous substances such as Cr, Ni, Mn, V, Cu, or F. The effects of these elements individually on humans and laboratory animals have been partially documented, as have the effects on workers of uncontrolled exposure to welding fumes. The National Institute of Occupational Safety and Health (NIOSH), U.S. Department of Labor, has prepared an unpublished criteria document draft for welding, brazing, and cutting. This document draws on existing data and information to develop criteria that could help establish standards to protect the safety and health of welders.

To help formulate standards for the mining industry, MSHA needs additional information specific to mining operations, such as the types and degree of welding performed, the electrodes used,

the amount of contamination generated by those electrodes and their constituents, and the nature of controls used to protect the welder. Much of this information requires in-mine documentation such as surveys of welding products used, interviews with welders, air monitoring, etc. No comprehensive studies of welding practice in the mining industry exist; however, limited surveys (1-2)³ have identified more than 300 electrode types, by either brand name or American Welding Society (AWS) designation, that have been or are being used in mines and surface shops. Most of the data are qualitative in that they neither indicate the relative amounts of each type used nor specify particular locations or environments where these electrodes are used. It can be surmised that shielded metal arc welding (SMAW)--popularly known as stick welding--with mild or low-alloy steel electrodes forms the bulk of the welding done. Nevertheless, welding is also performed with stainless steel and Ni-base alloys, and hardfacing and rebuilding are performed with highly alloyed Fe-, Ni-, or Co-base alloys.

Another source of information is contained in the air-sampling data collected by MSHA inspectors since 1974 while monitoring welders and maintenance workers in mines and mine shops. These data have been computerized, edited, and organized by the Bureau (3). They show that, based on the fraction of samples indicating constituents that exceed the respective threshold limit value, time-weighted average (TLV-TWA),⁴ the

²Arc-welding operations generate a mixture of smoke and gases. Vaporized metallic particles from the arc, generally in the form of oxides, agglomerate to form aerosols in the size range of about 0.01 to 50 μm . It is these fine particles, rather than gases, that one sees emanating from welding operations. Particles in the upper end of this range and larger settle out relatively quickly as dust, but the lighter particles may remain suspended in the air. The term "fume" is sometimes used to refer to the smoke plus gases, and sometimes it refers to only the fine particles generated. In this report, unless otherwise stated, fume will refer to only the airborne particulates and not to any gases generated during welding operations.

³Underlined numbers in parentheses refer to items in the list of references preceding the appendix.

⁴Threshold limit value, time-weighted average is defined (4) as "the time-weighted average concentration for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect." In this report, "TLV" will refer exclusively to this time-weighted average, expressed in milligrams per cubic meter.

principal contaminants are Co and Cr. The usefulness of these data is limited, however, because contaminant levels cannot be related to specific operations parameters such as electrode type, type of welding, ventilation, welding surface cleanliness, and related factors.

Bureau research (5) involved with the ventilation of air-borne contaminants from welding fumes in surface mines included data showing airborne contaminant levels from five low-alloy steel electrodes.

The presence of Cr in most of the higher alloy electrodes and its suspected carcinogenicity has led to several investigations of stainless steel electrode fumes (6-8), with emphasis on the detection of hexavalent Cr (Cr^{6+}), the suspected carcinogenic species. Typically, the fumes contained 4 to 6 wt pct total Cr, with 75 to 98 wt pct of this being water-soluble Cr^{6+} .

An extensive study of welding fumes and gases (9), in which all aspects of welding, cutting, and brazing fume production were investigated, produced generation

rate and chemical data for fumes from carbon- and low-alloy steel electrodes, three types of stainless steel electrodes, and an assortment of high-alloy or nonferrous electrodes. Total Cr content for fumes from type 316 stainless steel was 5.8 to 6.5 wt pct; no analyses for hexavalent Cr were made. An Ni content of 6.9 wt pct, from the fumes of an ENiCr, all-Ni electrode, was given also. Jenkins (8) listed Cr and Co contents of 14.2 and 24.7 wt pct, respectively, for fume from a Co-27 Cr-W hardfacing alloy and a Mn content of 17.1 wt pct from an Fe-13 Mn hardfacing alloy.

To supplement these data, and to provide data for specific electrodes that could be of use to mine inspectors, the Bureau endeavored to generate, collect, and analyze fumes from a variety of electrodes in a laboratory environment. The electrodes were selected from listings of those used in the mining industry, with emphasis placed on the more highly alloyed filler metals. This report describes the results of this investigation.

EXPERIMENTAL PROCEDURE

Fume generation experiments were performed in an enclosed welding chamber from which the fumes could be extracted for analysis. Details of the apparatus and procedure are given in a previous Bureau report (10). In brief, fumes generated during the welding of a bead onto a rotating steel plate were captured in or on filters situated in the exhaust airflow duct of the chamber. Fume generation rates, in terms of the weight of fume generated per minute of arc time, were determined from weighing fume-laden fiberglass filters. Samples for chemical analysis were obtained by brushing accumulated fume deposits from the surface of 25- μm (coarse porosity) cellulose paper filters. The Fe, Ni, Mn, Cu, Ti, Ca, and Al in the deposits were solubilized with a sulfuric acid leach, followed by fusion with Na_2O_2 for the acid insolubles. All but Ti were analyzed by AAS; Ti was analyzed colorimetrically. Sodium and potassium were acid leached and analyzed by AAS. Fluorine was determined

with a specific ion electrode in sodium solution. Silicon was analyzed gravimetrically, and oxygen was determined by Leco combustion. Chromium fractions were measured in two ways: Total Cr was extracted with an H_2SO_4 leach followed by Na_2O_2 fusion of the residue; the combined solutes were titrated. The second method for Cr analysis is essentially the basic leach described by Andrews (11), known as the INCO method (named for the International Nickel Co, where the method was developed). The initial step is a slightly alkaline water leach to extract soluble Cr^{6+} . From the residue, water-insoluble (actually slightly soluble) Cr^{6+} is then extracted by a caustic leach. The INCO method ends with an acid leach of this residue to extract Cr^{3+} . In the present study, some residue remained after the acid leach; this residue was Na_2O_2 -fused to extract the remaining Cr. All solutions were then acidified and analyzed by AAS. Total Cr was taken as the sum of the products of these four

steps. It is believed that the total Cr values derived by the first method (i.e., using H_2SO_4 and Na_2O_2) are more accurate than the total of the four separate analyses encountered in the INCO method; therefore, values from the former method are listed in the results. The apparatus was calibrated according to American Welding Society Standard Fl.2-79 (12).

Towards the end of the project, an arc-length controller was added to the system. This consisted of a Jetline⁵ model ALC 301 controller, designed for wire feed systems but adapted for SMAW. The voltage-controlled, motorized drive system (fig. 1) maintains a constant arc

⁵Reference to specific products does not imply endorsement by the Bureau of Mines.

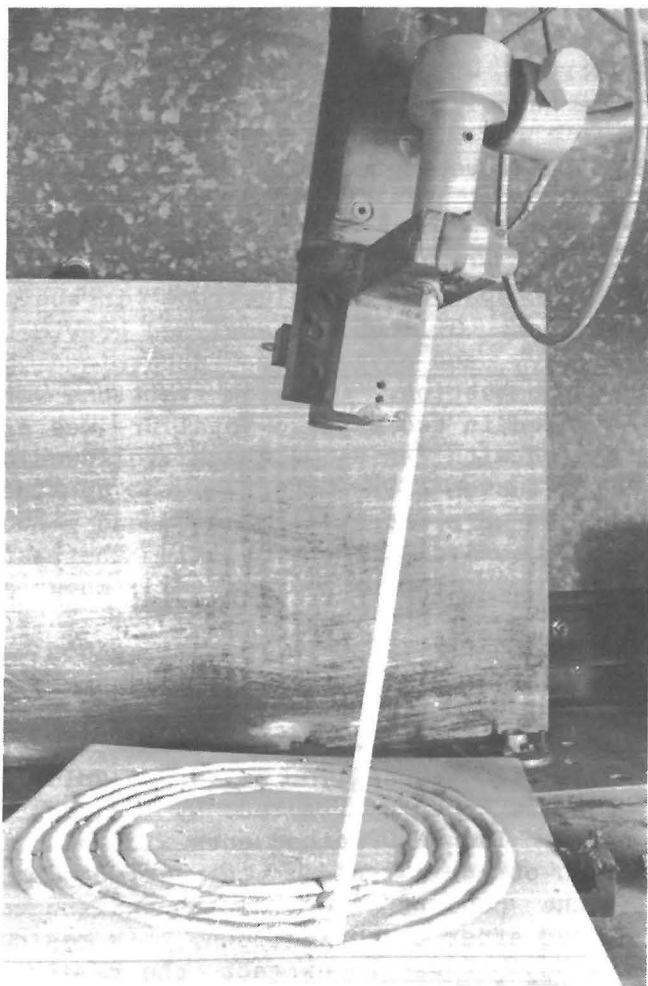


FIGURE 1.—Welding electrode positioned in automatic feed system installed in chamber. Weld beads on the mild-steel plate are produced by rotation of the plate under the electrode.

length while feeding the electrode to the arc at a fixed rate. The result of this modification was less variation in arc voltage for each electrode run and greater consistency of voltage values among electrodes.

The testing of wire electrodes utilized a commercial wire feed unit with the capability of coaxial gas shielding. A shielding gas of CO_2 was used with the solid-wire calibration electrode; no gas was used with the flux-cored arc welding (FCAW) wires tested.

Of the electrode types cited in mine surveys, the more highly alloyed varieties, which represent a greater hazard potential, and two of the more widely used low-alloy electrodes constituted the selection pool. The MSHA data cited previously suggested that electrodes high in Co or Cr should be chosen. Additionally, a high-Ni group and a Mn-containing group were chosen since those elements are considered hazardous. The low-alloy electrode fluxes contain fluoride, an ion also considered hazardous. Using the mine surveys, the following groups of SMAW electrodes were chosen for evaluation: AWS 5.4, E308-16; AWS 5.4, E310-16; AWS 5.13, ECoCr-A; AWS 5.15, ENiCr; an unclassified Fe-base, Mn-Cr surfacing alloy; AWS 5.1, E7018; and AWS 5.5, E11018-M. The compositions of the weld deposits specified for these alloy electrodes, sometimes referred to as filler metal specifications, are given in table 1. Component values for the Mn-Cr alloy weld deposits are ranges specified for those electrodes studied. One group of FCAW electrodes with compositions similar to this surfacing alloy was evaluated.

Within each group of SMAW electrodes, five brands were selected; three brands were studied within the FCAW group. Most of the brands were those appearing on mine survey listings. Except where noted, all electrodes within a group were the same size and were tested at approximately the same arc voltages and currents.

Each of the brands was tested by deposition of a weld bead onto a sandblasted mild steel plate. In actual welding operations, however, and in particular

TABLE 1. - Weld deposit compositions (filler metal specifications) for welding electrodes (13), weight percent

AWS code and electrode type	Co	Cr	Fe	Mn	Ni		Other ¹
A5.4:							
E308-16.....	NS..	18-21	Ba1	0.5-2.5	9	-11	2.0
E310-16.....	NS..	25-28	Ba1	1 -2.5	20	-22.5	2.0
A5.13:							
ECoCr-A.....	Ba1.	25-32	Ba1	2		3	10.9
A5.15:							
ENiCr.....	NS..	NS	5	1		85 ²	9.5
14 Mn-4 Cr ³	NS..	4- 5	8	.5-4.0	14	-16	.5
A5.1:							
E7018.....	NS..	.20	Ba1	1.60		.30	1.1
A5.5:							
E11018-M.....	NS..	.40	Ba1	1.3-1.8	1.25-	2.50	1.3

Ba1 Balance. NS Not specified.

¹Maximum.

²Minimum.

³Not classified by AWS; data supplied by manufacturers of electrodes used in this study.

hardfacing and rebuilding, welding is done in multiple layers of the weld filler metal. The weld alloy, rather than the original steel of the welded part, then becomes the substrate. To assess the effect of this new substrate on fume generation, a double-layer bead pad of the weld alloy was deposited onto a mild

steel plate. After sandblast cleaning, this pad served as the new substrate for fume generation tests of that same alloy, performed in the same manner as with the mild steel plate substrates. One brand from each of the five high-alloy SMAW groups was tested this way.

RESULTS

MILD STEEL SUBSTRATE

The data collected from the tests are the weight of the fume collected, the weight of the electrode consumed, the arc time, and the chemical analysis of the fume. Welding conditions such as voltage, current, plate speed, and electrode feed rate were recorded or derived for each test. For the alloy groups, two additional quantities, a maximum allowable fume exposure and an exposure rating, have been derived from the data.

Two quantities based on the weight of fume generated are the fume generation rate, FGR, and the fume weight per weight of electrode consumed, f_e . The FGR measures the fume generating tendencies of an electrode and is used to derive the exposure rating. Where the arc is operating intermittently, as during a work

shift, f_e may be more useful in estimating the amount of fume generated. In either case, the data apply to the operating conditions stated and, for the FGR at least, to the size of the electrode given.

Fume generation data for the electrode groups are listed in table 2. Each electrode brand has been given a code letter or letters. Replicates were measured on one of the brands, code D, to get an estimate of the repeatability of the experiments and analyses. Code D was chosen at random from among the electrodes in this group. Comparisons of the derived FGR and f_e values between the replicates and the original data set, using the Student t statistic (14) at the 90-pct confidence level, show no significant differences. The coefficients of variation (CV) of the data sets of code D, for both FGR and f_e

TABLE 2. - Fume generation data for electrodes

Code	Runs	Average		FGR,	SD,	f _e , pct	SD, pct
		Voltage, V	Current, A	mg/min	mg/min		
TYPE E308-16--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
A.....	5	23	171	394	51	0.88	0.10
B.....	4	24	175	478	13	1.21	.18
C.....	5	24	173	514	27	1.31	.04
D.....	5	22	173	422	58	1.06	.14
	5	23	176	396	30	.95	.07
	6	23	174	415	27	1.04	.07
E.....	5	23	173	472	31	1.22	.07
Mean.....	NAp	23	174	440	55	1.09	.16
TYPE E310-16--dc, ELECTRODE POSITIVE; 4.76-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
F.....	3	24	163	446	26	1.11	0.06
G.....	6	23	166	540	37	1.47	.11
H ¹	6	24	164	659	31	2.17	.13
I.....	6	23	165	455	33	1.20	.13
J.....	5	25	160	527	32	1.39	.10
Mean.....	NAp	24	164	534	84	1.51	.40
TYPE ECoCr-A--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 45-s ARC TIME							
K.....	5	26	140	766	59	2.58	0.20
L.....	5	26	137	571	77	1.77	.32
M.....	6	25	134	713	23	2.31	.07
N.....	6	24	139	1,086	74	4.29	.32
O ²	5	28	176	1,041	46	2.86	.11
Mean ³	NAp	25	138	795	204	2.79	1.01
TYPE ENiCl--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
P.....	6	24	135	612	12	2.08	0.06
Q.....	6	22	140	538	13	1.90	.08
R.....	4	24	143	598	12	1.78	.06
S.....	6	24	138	560	18	2.14	.11
T.....	5	23	139	461	16	1.38	.06
Mean.....	NAp	23	139	554	54	1.88	.28
14 Mn-4 Cr SURFACING ALLOY--dc, ELECTRODE POSITIVE; 4.76-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 20-s ARC TIME							
U.....	4	24	200	3,010	140	8.08	0.37
V.....	3	24	199	3,280	82	9.16	.10
W.....	5	24	198	3,170	270	7.81	.43
X.....	5	24	197	3,280	200	8.82	.50
Y.....	6	24	196	2,380	250	7.13	.55
Mean.....	NAp	24	198	2,980	420	8.16	.79

See explanatory notes at end of table.

TABLE 2. - Fume generation data for electrodes--Continued

Code	Runs	Average		FGR, mg/min	SD, mg/min	f _e , pct	SD, pct
		Voltage, V	Current, A				
TYPE E7018--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED; 1-min ARC TIME							
CC.....	6	24	161	459	30	1.55	0.10
DD.....	5	24	159	515	20	1.81	.08
EE.....	6	24	165	653	40	2.17	.15
FF.....	6	24	158	475	21	1.62	.07
GG.....	6	24	164	511	21	1.70	.08
Mean.....	Nap	24	161	523	75	1.77	.24
TYPE E11018-M--dc, ELECTRODE POSITIVE; 3.97-mm CORE DIAM; 280-mm/min TRAVEL SPEED, 1-min ARC TIME							
HH.....	6	24	163	445	16	1.46	0.06
II.....	6	24	160	561	12	1.96	.05
JJ.....	6	24	160	518	15	1.72	.06
KK.....	6	24	163	560	20	1.90	.06
LL.....	6	24	158	513	34	1.70	.10
Mean.....	Nap	24	161	520	47	1.75	.19
Mn-Cr SURFACING ALLOY FLUX-CORED WIRE--dc, ELECTRODE POSITIVE; 2.78-mm DIAM, 38-mm WIRE STICKOUT; 430-mm/min TRAVEL SPEED; 2,200-mm/min WIRE FEED; 1-min ARC TIME; NO SHIELD GAS							
Z ⁴	6	30	288	5,070	200	6.2	0.24
BB ⁴	5	29	317	4,320	190	5.2	.23
Mean.....	Nap	30	303	4,700	530	5.7	.73
AA ⁵	6	30	287	5,410	620	6.1	.70

f_e Fume weight per weight
of electrode consumed.

FGR Fume generation rate.

Nap Not applicable.

SD Standard deviation.

¹Composite core.

²4.76-mm core diameter.

³Excludes code 0 data.

⁴Nominally 15 pct Mn, 4 pct Cr.

⁵Nominally 1.5 pct Mn, 16 pct Cr.

determinations, vary from 6.5 to 13.7 pct. These are similar to values computed for the other brands in this group.

For the most part, the results presented in the tables are straightforward. Code H electrodes, in the type E310-16 series, give higher fume generation data than do others in the group. This may be due to their unique construction. Unlike the solid filler core of the other electrodes, code H electrodes consist of a hollow tube filled with granular metal. This construction results in a larger surface area per unit weight of filler metal, thus generating more fume.

Because the code 0 electrodes are of a larger diameter than are the other type ECoCr-A electrodes, they were tested at commensurately higher voltage and current settings, and their data were not included in calculating the means for the group. However, its FGR value, if reduced by the ratio of the group electrode cross section to its own cross section, is not significantly different from the group mean. Note also that its fume fraction, f_e , which effectively corrects for the difference in size, is quite close to that of the group mean.

Within each group, the mean FGR and f_e values were calculated using all of the respective data points; thus, in table 2, for example, the group FGR of 440 mg/min is the mean of 35 data points, rather than the mean of the 7 FGR values listed. Better than 94 pct of the data points in each group fell within two standard deviations of the mean.

Fume compositions of each of the electrode brands are listed in table 3. Only those elements appearing at 1 wt pct or more for at least one brand are listed. Both total and hexavalent Cr values are listed where significant. Typically, 10 pct or so of the Cr^{6+} is water insoluble; these data are not listed separately.

In some cases, the fume composition is not totally defined. Where oxygen analyses were made, as for electrode groups E308-16, E7018, and E11018-M, the individual elemental fractions were totaled to determine if 100 pct of the fume composition could be accounted for. Of these electrodes, constituent fractions in only codes A, B, D, and E totaled to >100 pct. Constituent fractions in codes EE and FF, and all of the type E11018-M electrodes, added to <90-pct total, while the others within those three groups totaled between 90 and 95 pct. Estimates of the oxygen contents⁶ in the fumes of the remaining electrodes, for which analyses were not made, indicated probable material balances of >95 pct for most of the electrodes.

Variability of the data was estimated from the replicate data taken on the code D electrodes. It is expressed as the coefficient of variation (CV), which is the standard deviation (SD) divided by the mean. CV values were below 5 pct for all but three of the elements analyzed for in these fumes; Ti at 8.6 pct, Ca at 13.3

pct, and Na at 13.4 pct. These figures represent the combined precisions of the fume collection and chemical analysis.

Among the brands of electrodes of a particular type, the variation is greater due to variations primarily in the flux formulations and to a lesser extent in the filler metal compositions. In the following treatment of two indices of fume hazard, elements with similar chemical properties, such as the alkaline earths, are grouped, thereby minimizing some of the compositional differences.

A relative exposure index was used in a previous report on welding fumes (10) to translate the fume constituent data into a more useful measure of the effect of the fume on the welder. This index is developed as follows: the exposure of the welder to individual components of the fume, E_i , in terms of milligrams of the component per cubic meter of air, is

$$E_i = C(\text{mg}/\text{m}^3)f_{i, \text{fume}}, \quad (1)$$

where C is the total fume exposure and $f_{i, \text{fume}}$ is the fraction of the fume made up by component i . The maximum allowable exposure to a particular component is governed by the threshold limit value (TLV). By setting $E_{i, \text{max}} = \text{TLV}_i$, a maximum allowable total fume exposure, $C_{i, \text{max}}$, can be calculated for each constituent as

$$C_{i, \text{max}} (\text{mg}/\text{m}^3) = \frac{E_{i, \text{max}}}{f_{i, \text{fume}}} = \frac{\text{TLV}_i}{f_{i, \text{fume}}}. \quad (2)$$

The lowest $C_{i, \text{max}}$ value among those calculated for each element becomes the exposure index, C_m , for that electrode. In other words, it determines the lowest total fume exposure that will cause the welder to be overexposed to one of the fume constituents. Table 4 lists the TLV's used to calculate the exposure indices. Although significant levels of Na and K occur in the fumes, the absence of TLV's for these elements precluded $C_{i, \text{max}}$ calculations for them. Sr was, however, included, particularly for the code S fume. A value of $1.0 \text{ mg}/\text{m}^3$, interpolated from the TLV's of Ca and Ba, was used in place of a published TLV. For these

⁶Oxygen levels were based on the following oxides present, where applicable: Al_2O_3 , BaO , CO_3 , CaO , CoO , Cr_2O_3 , CrO_3 , Fe_2O_3 , K_2O , MnO , Na_2O , NiO , SiO_2 , SrO , TiO_2 , and WO_3 . Those elemental fractions thought to form fluorides, calculated in the order KF , NaF , BaF_2 , SiF_2 , and CaF_2 , were not included in the oxide calculations.

TABLE 3. - Chemical composition of fumes generated from electrodes, weight percent

Code	Al	Ba	Ca	Co	¹ Cr	² Cr ⁶⁺	F	Fe	K	Mn	Na	Ni	Si	Sr	Ti
TYPE E308-16															
A.....	0.5		5.5		9.4	5.5	8.8	18.1	10.7	4.9	4.1	1.7	5.4		2.4
B.....	.8		4.9		9.2	4.4	6.3	19.5	11.0	9.6	2.8	2.0	4.8		2.6
C.....	.4		3.2		9.4	5.5	7.8	17.3	13.0	6.4	4.8	1.9	4.5		2.7
D.....	.3		3.6		9.9	³ 5.2	8.0	17.6	8.0	6.7	6.3	1.9	5.3		2.2
	.3		2.8		9.2	³ 5.2	7.8	17.5	8.7	6.6	8.0	1.8	5.4		2.6
	.3		3.0		9.3	³ 5.2	7.3	18.3	8.5	6.4	6.5	1.9	5.1		2.5
E.....	1.0		3.3		8.7	4.8	7.1	18.8	11.9	7.5	3.5	2.0	4.4		2.4
Mean.....	.5		3.8		9.3	5.1	7.6	18.2	10.2	6.9	5.1	1.9	5.0		2.5
SD.....	.26		1.0		.36	.48	.79	.79	1.9	1.4	1.8	.11	.42		.17
TYPE E310-16															
F.....	0.7		2.2		11.6	4.6	6.5	14.8	12.8	8.1	1.6	4.8	3.7		3.1
G.....	.4		1.7		11.2	4.8	5.4	17.8	10.2	8.6	3.9	5.9	3.7		1.9
H.....	.6		2.9		13.9	4.5	5.9	18.8	4.6	6.4	4.7	6.1	4.4		1.1
I.....	.6		2.7		11.6	5.5	7.0	15.3	17.6	8.3	3.4	5.2	4.5		2.8
J.....	1.0		5.3		12.1	6.0	9.3	14.9	9.6	6.2	3.4	5.1	3.4		2.0
Mean.....	.6		3.0		12.1	5.1	6.8	16.3	11.0	7.5	3.4	5.4	3.9		2.2
SD.....	.23		1.4		1.1	.64	1.5	1.8	4.8	1.1	1.1	.55	.48		.79
TYPE ECoCr-A															
K.....	0.2		1.3	28.1	18.4	1.4	3.6	3.3	0	7.6	3.1	1.4	2.7		0.8
L.....	1.1		2.4	23.2	15.7	2.3	7.3	3.3	.1	2.8	6.6	1.2	.8		2.4
M.....	.7		2.4	21.6	13.6	4.3	6.1	2.8	6.8	.3	4.3	1.2	4.2		1.7
N.....	.4		1.5	26.8	15.4	1.4	3.1	3.2	4.4	4.0	1.5	.1	4.0		1.6
O.....	NA		2.8	22.9	17.1	4.1	5.5	2.6	6.2	1.0	3.9	1.0	4.3		1.5
Mean.....	.6		2.1	24.5	16.0	2.7	5.1	3.0	3.5	3.1	3.9	1.0	3.2		1.6
SD.....	.37		.63	2.8	1.8	1.4	1.8	.32	3.3	2.9	1.9	.50	1.5		.57
TYPE ENiCI															
P.....	0.2	22.7	19.2				6.7	2.1		2.0	4.6	9.8	2.6	0.2	
Q.....	.2	28.7	8.0				5.5	2.3		.3	3.9	18.0	1.4	1.7	
R.....	6.5	23.9	18.0				6.3	1.2		.4	4.8	5.2	2.0	2.1	
S.....	3.1	23.0	1.0				NA	2.9		.7	4.8	11.5	2.7	20.3	
T.....	.3	39.1	12.3				NA	2.0		.2	5.7	5.7	3.2	.5	
Mean.....	2.0	27.5	11.7				6.2	2.1		.7	4.8	10.0	2.4	5.0	
SD.....	2.8	6.9	7.5				.61	.61		.75	.64	5.2	.69	8.6	

See explanatory notes at end of table.

NOTE.--No entry in a column indicates that element was not a fume constituent.

TABLE 3. - Chemical composition of fumes generated from electrodes, weight percent--Continued

Code	Al	Ba	Ca	Co	¹ Cr	² Cr ⁶⁺	F	Fe	K	Mn	Na	Ni	Si	Sr	Ti
14 Mn-4 Cr SURFACING ALLOY															
U.....					1.9		NA	35.4		24.4	2.0	3.1	0.6		
V.....					1.6		NA	33.1		36.0	1.0	.3	1.8		
W.....					1.3		NA	36.8		26.6	1.7	2.9	2.3		
X.....					1.7		0	37.9		25.5	.8	2.7	.6		
Y.....					2.1		1.1	30.2		29.4	1.1	1.3	2.2		
Mean.....					1.7		.6	34.7		28.4	1.3	2.1	1.5		
SD.....					.30		.78	3.1		4.6	.50	1.2	.83		
TYPE E7018															
CC.....	0.7		10.8				1.2	29.1	14.6	8.6	3.1		5.1	NA	
DD.....	.6		11.0				.9	37.0	12.3	9.5	2.9		6.0	NA	
EE.....	1.1		11.3				0	25.3	5.0	3.9	2.7		1.3	NA	
FF.....	.4		10.8				9.3	24.3	11.1	5.5	1.9		4.9	NA	
GG.....	.2		11.4				5.8	31.9	6.7	4.5	3.9		6.3	1.0	
Mean.....	.6		11.1				3.4	29.5	9.9	6.4	2.9		4.7	1.0	
SD.....	.36		.28				4.0	5.2	4.0	2.5	.72		2.0	NAP	
TYPE E11018-M															
HH.....			13.0				4.7	24.5	6.8	14.5	4.4		2.0	1.2	
II.....			6.3				2.0	33.1	6.6	6.5	3.4		6.1	0	
JJ.....			10.6				8.1	33.0	.7	6.0	4.9		.4	0	
KK.....			10.1				5.6	36.6	3.5	6.1	5.0		2.7	0	
LL.....			12.9				.9	26.1	7.3	6.6	4.1		1.5	1.1	
Mean.....			10.6				4.3	30.7	4.4	7.9	4.4		2.5	.5	
SD.....			2.7				2.9	5.1	2.9	3.7	.65		2.2	.63	
Mn-Cr SURFACING ALLOY FLUX-CORED WIRE															
Z.....					1.7		1.7	43.4		22.3		2.0			
BB.....					1.7		2.4	43.9		26.6		.4			
Mean.....					1.7		2.0	43.7		24.5		1.2			
AA.....					10.5		.1	54.8		3.1		.3			

NA Not analyzed.

¹Determined by acid leach-titration.

NAP Not applicable.

²Determined by INCO method.

SD Standard deviation.

³Single analysis run on separate sample.

NOTE.--No entry in a column indicates that element was not a fume constituent.

elements, the exposure value was calculated as

$$C_{i,max} = [\Sigma(f_{i,fume}/TLV_i)]^{-1}. \quad (3)$$

The resulting relative exposure indices for the electrode brands are given as C_m values in table 5.

A second index, the exposure rating, R , is derived from C_m and the FGR, as

$$R(m^3/min) = \frac{FGR}{C_m}. \quad (4)$$

If taken literally, it represents the amount of fresh air per minute needed to dilute the fume being generated to a safe level. It is essentially equivalent to the nominal hygienic air requirements (NHL) developed in Sweden to rate the fume hazards of electrodes numerically (14-15). The NHL, however, combines all of the components, using equation 3,

thereby leading to higher values of the ratings. Also, lower TLV's, such as for Cr or Ni, are used. The NHL is given in cubic meters per hour. Because of these differences, the exposure rating R is used in this report. Values for the electrode brands appear in table 5. According to this ranking, the ECoCr-A

TABLE 4. - Threshold limit values (TLV's) for fume constituents (4), milligrams per cubic meter

	TLV		TLV		TLV
Al....	10	Cr ⁶⁺ ..	0.05	Na....	(²)
Ba....	.5	F.....	2.5	Ni....	1
Ca....	1.4	Fe....	5	Si....	³ 2.8
Co....	.1	K.....	(²)	Sr....	(²)
Cr....	.5	Mn....	1	Ti....	(⁴)

¹Based on 2-mg/m³ TLV for CaO.

²None established in reference.

³Based on 6-mg/m³ TLV for amorphous SiO₂.

⁴TLV for TiO₂ deleted from reference.

TABLE 5. - Exposure index (C_m) and exposure rating (R) values for welding electrodes

Group and code	C_m , mg/m ³	R , m ³ /min	Group and code	C_m , mg/m ³	R , m ³ /min	Group and code	C_m , mg/m ³	R , m ³ /min
E308-16:			ECoCr-A---Con:			Mn-Cr buildup		
A.....	1.1	370	Mean ¹	0.40	1,980	wires---Con:		
B.....	1.2	400	2 SD.....	±.10	±1,420	BB ²	3.8	1,150
C.....	.89	580	ENiCI:			Mean.....	4.1	1,140
D.....	.92	440	P.....	1.8	340	2 SD.....	±1.0	±30
E.....	.94	500	Q.....	1.6	340	AA ³	4.8	1,140
Mean.....	1.0	460	R.....	1.7	350	E7018:		
2 SD.....	±.27	±170	S.....	1.5	370	CC.....	11.6	40
E310-16:			T.....	1.2	390	DD.....	10.5	49
F.....	1.1	410	Mean.....	1.6	360	EE.....	19.8	33
G.....	1.0	520	2 SD.....	±.26	±43	FF.....	18.2	26
H.....	1.1	590	Mn-Cr buildup:			GG.....	15.7	32
I.....	.92	500	U.....	4.1	730	Mean.....	15.2	36
J.....	.84	630	V.....	2.8	1,180	2 SD.....	±8.1	±18
Mean.....	1.0	530	W.....	3.8	840	E11018-M:		
2 SD.....	±.23	±170	X.....	3.9	840	HH.....	6.9	64
ECoCr-A:			Y.....	3.4	700	II.....	15.1	37
K.....	.36	2,150	Mean.....	3.6	860	JJ.....	13.6	38
L.....	.43	1,320	2 SD.....	±1.0	±380	KK.....	13.7	41
M.....	.46	1,540	Mn-Cr build-			LL.....	11.1	46
N.....	.37	2,910	up wires:			Mean.....	12.1	45
O.....	.44	2,380	Z ²	4.5	1,130	2 SD.....	±6.5	±22

2 SD 2 standard deviations.

¹Excludes code 0 data. ²Nominally 15 pct Mn, 4 pct Cr.

³Nominally 1.5 pct Mn, 16 pct Cr.

electrodes, as a group, are 55 times more hazardous to use than the carbon steel E7018 electrodes. Included in the data are two standard deviation (2 SD) values calculated from the data listed. Although not strictly justifiable from the small number of samples used, this statistic should encompass most of the electrode brands not tested.

The data in figures 2 through 5 were tested to determine fits to curves of the form $f_f = a_0 + a_1 f_e$ and $f_f = a_0 + a_1 f_e^{1/2} + a_2 f_e$, where f_f and f_e are the elemental fractions in the fume and electrode, respectively. Although the second curve gave slightly better fits for each of the elements, negative values for the coefficient a_1 for Cr and Fe argued in favor of linear fits for these data. Figure 2 plots data for five of the electrode groups in which Cr was a contributor to the fume. The least-squares fit shown is

$$f_{Cr, fume} = -0.31 + 0.66 f_{Cr, elec}, \quad (5)$$

with deviations of about 24 pct. All fume fractions in equations 5 through 10 are in weight percent. More precise fits result from separately grouping the ECoCr-A or the stainless steel electrodes

with Mn-Cr electrodes, giving for the ECoCr-A group

$$f_{Cr, fume} = -0.11 + 0.75 f_{Cr, elec}, \quad (6)$$

and for the stainless steel E308-16 and E310-16 electrodes combined

$$f_{Cr, fume} = -0.054 + 0.57 f_{Cr, elec}. \quad (7)$$

Shown also in the figure are mean values of the weld-metal specifications for Cr in these alloy groups. These values, representing the Cr level in the weld deposit, are the only Cr fractions generally available.

Levels of hexavalent Cr in the fumes did not follow a pattern with respect to total Cr content in the electrode. The valence of the Cr is sensitive to the flux composition, which is quite complex for these electrodes.

A linear fit to the Fe data (fig. 3) is given by

$$f_{Fe, fume} = 0.916 + 0.45 f_{Fe, elec}. \quad (8)$$

Again, scatter is significant at about 30 pct. The weld-metal specification values are shown also. The Mn and Ni data are described by the relations

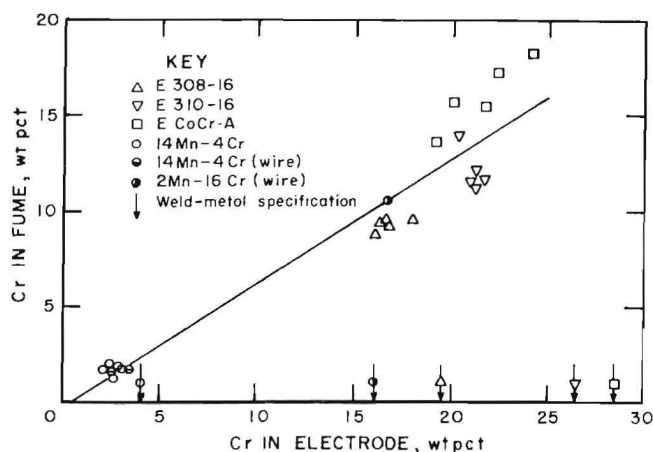


FIGURE 2.—Chromium fraction in fume as function of Cr content of electrode, including flux coating. Welding onto mild-steel plate.

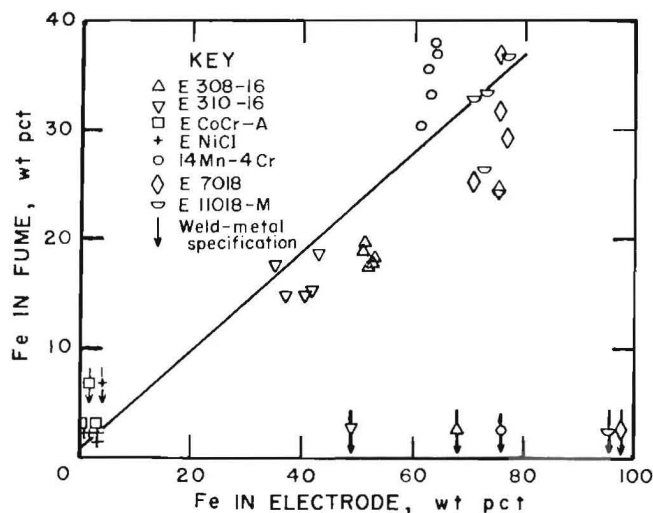


FIGURE 3.—Iron fraction in fume as function of Fe content of electrode, including flux coating. Welding onto mild-steel plate.

$$f_{\text{Mn}, \text{fume}} = -0.99 + 4.60 f_{\text{Mn}, \text{elec}}^{1/2} + 0.57 f_{\text{Mn}, \text{elec}}, \quad (9)$$

and

$$f_{\text{Ni}, \text{fume}} = -0.78 + 1.59 f_{\text{Ni}, \text{elec}}^{1/2} - 0.04 f_{\text{Ni}, \text{elec}}, \quad (10)$$

respectively. Figures 4 and 5 give the data and the weld-metal specification values. Mn comes the closest to matching these values in terms of the total electrode content. Its propensity to fume is substantially greater than that of the other metals shown, while Ni displays the least. The curves, combined in figure 6, show that these metals fume in ascending order as Ni, Fe, Cr, and Mn, roughly in proportion to their vapor pressures.

Because Co was not present in the other electrodes, the data for it were not plotted. The mean ratio of fume to electrode fractions for the five ECoCr-A

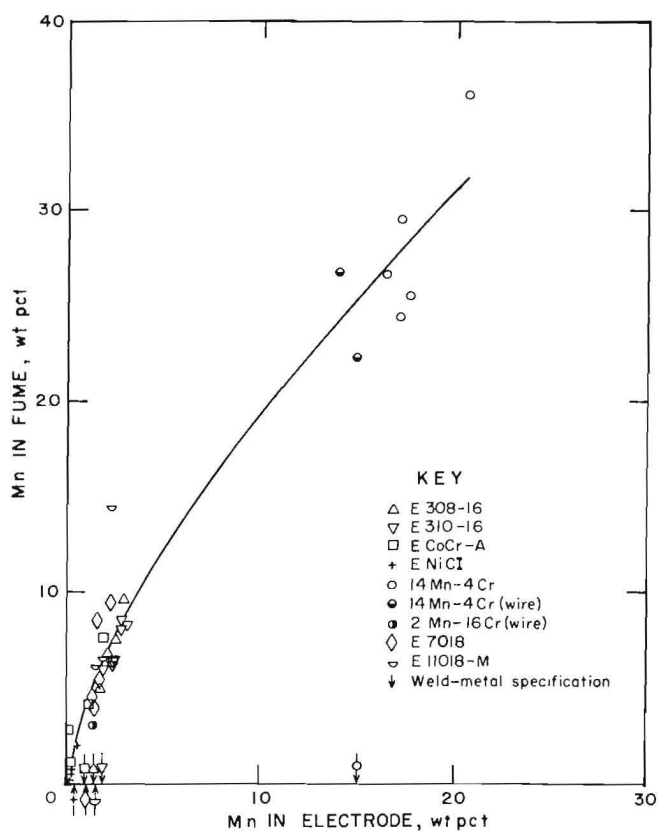


FIGURE 4.—Manganese fraction in fume as function of Mn content of electrode, including flux coating. Welding onto mild-steel plate.

electrodes is 0.54 ± 0.06 . If its fuming rate were linear with electrode content, Co would fall between Fe and Cr in fuming propensity. It does not follow in order of its vapor pressure, which is lower than that of Ni.

Partly because of the low fuming potential of Ni, the exposure index for the ENiCr electrodes was determined primarily by the Ba content of the fume, with secondary contributions from Sr and Ca. Although the fuming potentials for these elements, as determined by ratios of fume to electrode fractions, were

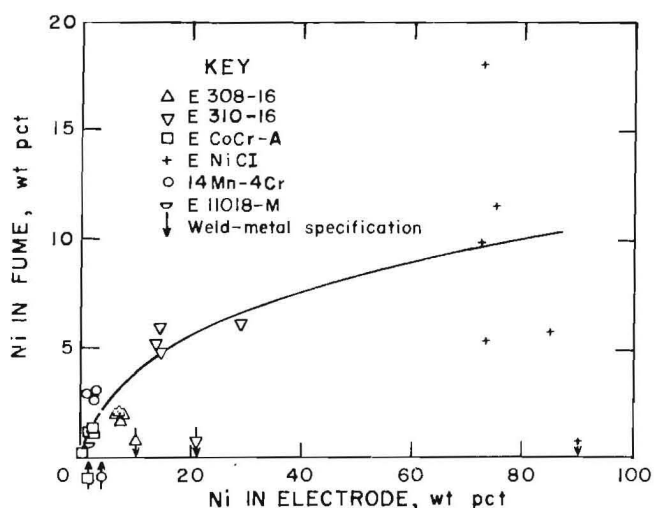


FIGURE 5.—Nickel fraction in fume as function of Ni content of electrode, including flux coating. Welding onto mild-steel plate.

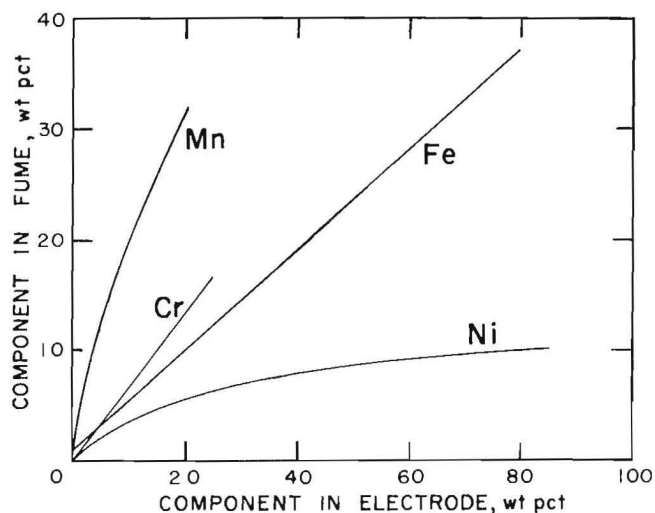


FIGURE 6.—Comparison of elemental components of fume to their respective contents in electrode.

substantially higher than for the filler metal components, the scatter was too great to be of use in predicting fume contents of untested electrodes.

ALLOY SUBSTRATE

The components of interest in the fumes of electrodes deposited onto double-layer alloy deposits (the substrate) are those found in the deposited filler metal. Fume compositions for the five electrodes tested this way appear in table 6. Except for hexavalent Cr, elements not exceeding 1 pct in the fume from mild steel welding were not analyzed for in the alloy welding fumes. Below each element fraction in the table is the ratio

of it to the corresponding mild steel weld component from the fume of the same electrode code. The uncertainties are calculated from the code D replicate data (table 3) using the t statistic. Values for hexavalent Cr and Co were estimated at ± 9.5 and ± 6.3 wt pct, respectively. In only a few cases do the results indicate a significant increase in the component fraction arising from the alloy substrate. The 9-pct rise in Co and a 16-pct rise in Cr in the code L electrode fume are troublesome in terms of welder exposure because of their already high level in the fume. The other elements showing large fractional increases are at low enough levels as to cause minimal concern.

TABLE 6. - Chemical composition of fumes generated from electrodes weld-deposited onto double-layer alloy substrates, weight percent

	E		I		L		S		Y	
	Fume	Ratio ¹	Fume	Ratio ¹	Fume	Ratio ¹	Fume	Ratio ¹	Fume	Ratio ¹
Co.....	NA	NA	NA	NA	25.4	1.09 \pm 0.07	NA	NA	NA	NA
² Cr.....	8.7	1.0 \pm 0.1	12.5	1.08 \pm 0.1	18.2	1.16 \pm .11	NA	NA	2.1	1.0 \pm 0.1
Cr ⁶⁺	4.2	.88 \pm .08	4.8	.87 \pm .08	2.0	.87 \pm .08	NA	NA	.36	1.4 \pm .1
Fe.....	17.6	.94 \pm .05	16.2	1.06 \pm .06	2.2	.67 \pm .04	2.7	0.93 \pm 0.05	30.8	1.02 \pm .06
Mn.....	7.2	.96 \pm .05	7.8	.94 \pm .05	.12	.04 \pm .00	NA	NA	29.2	.99 \pm .05
Ni.....	2.8	1.4 \pm .1	5.6	1.1 \pm .1	1.1	.92 \pm .07	10.4	.90 \pm .07	2.5	1.9 \pm .1
Si.....	4.2	.95 \pm .06	3.8	.84 \pm .06	NA	NA	1.7	.63 \pm .04	3.5	1.6 \pm .1

NA Not analyzed.

¹Alloy-generated component to mild-steel-generated component.

²Determined by acid leach-titration.

DISCUSSION

The exposure indices determined for the electrodes can be useful in a number of ways. The mining personnel responsible for specification of welding consumables could use these data to guide their selection of electrodes. Often, more highly alloyed austenitic stainless steel fillers are used to repair quenched-and-tempered steel structural components because they are considered more "forgiving" to less than optimum welding practices (16). The order of magnitude difference in exposure indices between the stainless steels and the E7018

or E11018-M steels should bias the selection towards the leaner electrodes. (It might be noted that a t statistic test shows no significant differences between the indices of E308-16 and E310-16 or between E7018 and E11018-M. A larger sampling might confirm the slight differences seen in the table.)

Knowledge of relative exposure hazards of the various types of electrodes would also alert the welder to take extra precautions during welding when using electrodes with higher exposure indices. Those with knowledge of any total fume

exposures recorded during previous operations could use the C_m ratings to judge whether their procedures were adequate to prevent overexposures.

Mine inspectors could also take advantage of the C_m index. It is current practice that fume samples taken during monitoring of welders are weighted at the field stations where total fume exposures are determined. Chemical analyses, however, which are much more time consuming, are performed at only one or two locations, leading to a substantial backlog in many cases. If the total fume exposures could be screened using the C_m values, with only those samples approaching C_m being sent on for analysis, this burden of extensive analyses might be relieved. For instance, if a field inspector determined the exposure to a miner using an Mn-Cr buildup electrode to be less than about 2 mg/m^3 , he could forgo the chemical analysis with the expectation that no overexposures to the individual components had occurred.

The use of equations 7 through 10 to predict the fume fractions of the respective elements is restricted by the general unavailability of total electrode composition. Usually only the filler-metal composition, the AWS generic specification ranges, or the typical weld deposit composition is known; flux compositions tend to be proprietary information.⁷ Figures 7 and 8 show curves based on best fits of fume component to weld-metal specification values, either the means of the ranges given in the AWS specifications (13) or the values 14 pct Mn and 4 pct Cr for that group of electrodes. The scatter bands are fit to t-distribution errors of the mean fume component. Values predicted from these relationships could then be used simply

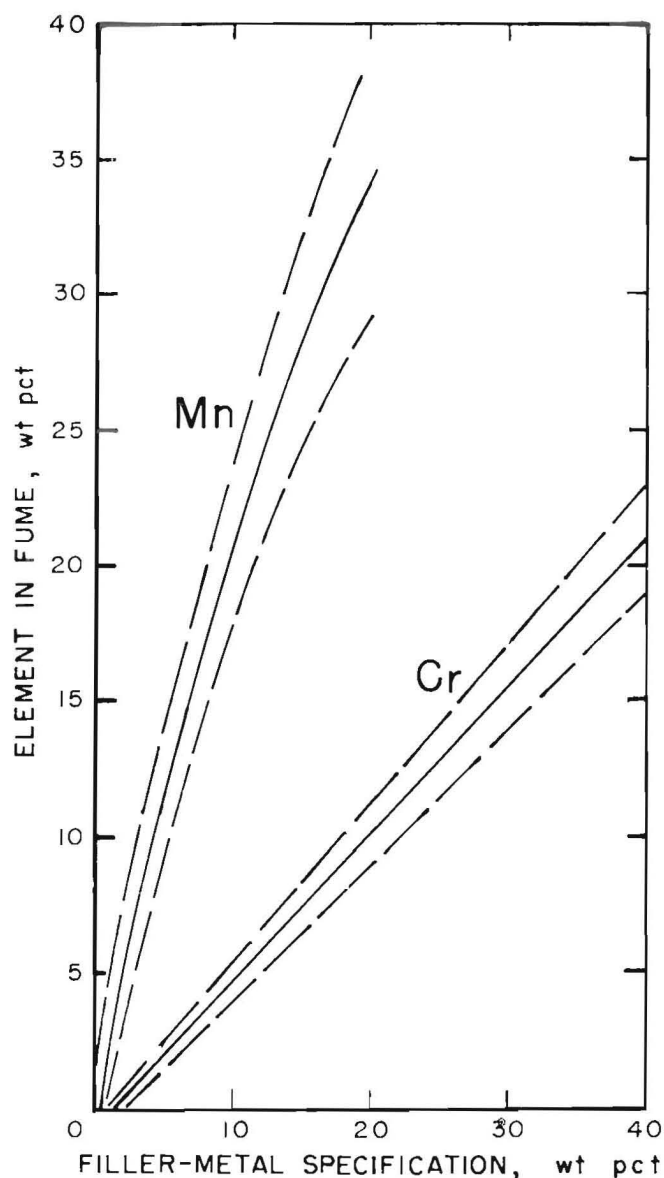


FIGURE 7.—Variation of Cr and Mn content of fume with filler metal specification, excluding flux coating. Dashed lines represent error estimates.

to calculate C_m indices for any electrode not included in these tests.

Of the nonmetallic elements, F, as fluoride, generates the most interest. The levels found in the present studies of types E7018 and ENiCl, 13 to 15 pct and 10 pct, respectively, are significantly

⁷The establishment of OSHA's Hazard Communication Standard may make this information more available in the form of Material Safety Data Sheets.

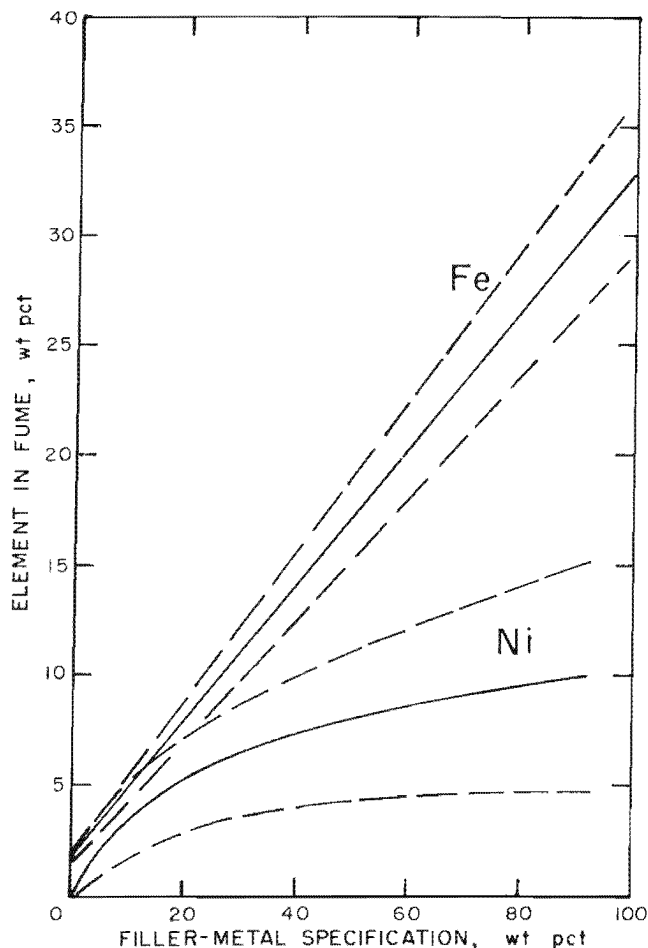


FIGURE 8.—Variation of Fe and Ni content of fume with filler metal specification, excluding flux coating. Dashed lines represent error estimates.

below those reported in the Battelle study (9). The value of 17.2 wt pct reported by Battelle for an E316-16 stainless steel electrode is much higher than the values in table 2 for similar flux covers. Miller and Jones (7), however, report levels of 6.6 to 9.5 wt pct for types E318-16 and E347-16 electrodes, which are more nearly in line with the present results. These differences appear to be due to the analytical techniques used: wet chemical analysis in the case of the Battelle study and ion-specific electrodes for this work and that of Miller and Jones.

Weld deposition onto alloy-layer substrates appeared to have some effect, but in only a few cases could they be considered significant. Deviations of ratios of alloy-layer to mild steel fume fractions from a value of one were considered real only if they exceeded the estimated error. Nine of the ratios in table 6 were thus taken to indicate no effect of substrate composition. Electrodes E, I, and L showed changes in their C_m values as a result of the alloy layer base. The two stainless steel indices increased to 1.1 and 1.0 mg/m^3 , respectively, due to the reduced hexavalent Cr. The Co-base code L index dropped to 0.39 mg/m^3 . Large-percentage increases in fume components such as with Cr^{6+} and Ni in the code Y fume are of minimal concern because of the low absolute levels involved.

SUMMARY AND CONCLUSIONS

This report documents the collection of fume generation and composition data taken from the weld deposition of the following groups of electrodes used in the mining industry: AWS types E308-16 and E310-16 stainless steel, ECoCr-A Co-Cr hard-facing alloy, ENiCl Ni, an Mn-Cr buildup alloy, E7018 carbon steel, and E11018-M low-alloy steel. Included in the data are the FGR's, the fume weight to electrode weight ratio, and the chemical composition of the fumes. Two exposure indices were derived from these data: C_m , the relative exposure index, which gives a maximum allowable total

fume exposure; and R, the exposure rating, which takes into account both the composition and volume of fume produced. High R values would alert the welder to take extra precautions while welding to avoid excessive fume exposures. Purchasing agents could use low values as a criterion for selection of electrodes, other physical or mechanical properties being equal. Mine inspectors could use the C_m data as a screening criterion to establish the necessity for performing more protracted and expensive chemical analyses of welding-fume samples.

Of the electrode groups tested, the ECoCr-A hard-facing alloys produced the lowest C_m and highest R values, a result of the high Co fraction in the fume. The exposure rating for the carbon steel E7018 electrodes was, by contrast, lower by more than a factor of 50. Curves fit to the data are given by which estimates of Cr, Ni, Mn, and Fe fume fractions

can be made for untested electrodes if the composition or weld-metal specifications are known.

The substrate metal composition had some effect on the fume composition, as determined by welding onto deposited alloy layers; however, only for the ECoCr-A electrode was the effect significantly detrimental.

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APPENDIX.--NOMENCLATURE

AAS	atomic absorption spectroscopy
C	total fume exposure
$C_{i,max}$	maximum allowable total fume exposure for a given element, i
C_m	maximum allowable total fume exposure for an electrode
CV	coefficient of variation
E_i	exposure to individual fume component
FCAW	flux-cored arc welding
f_e	fume weight per weight of electrode consumed
FGR	fume generation rate
$F_{i,elec}$	fraction of electrode made up by component, i
$F_{i,fume}$	fraction of fume made up by component, i
NHL	nominal hygienic air requirement
R	exposure rating
SD	standard deviation
SMAW	shielded metal arc welding
TLV	threshold limit value